

EVALUATION AND IMPROVEMENT OF THE PROTOTYPING PROCESS  
IN ELECTRONIC PRODUCT DEVELOPMENT

by

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S.M. Massachusetts Institute of Technology (1989)

SUBMITTED TO THE DEPARTMENTS OF MANAGEMENT AND MATERIALS  
SCIENCE AND ENGINEERING IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREES OF

MASTER OF SCIENCE IN MANAGEMENT

and

MASTER OF SCIENCE IN MATERIALS SCIENCE AND ENGINEERING

IN CONJUNCTION WITH THE LEADERS FOR MANUFACTURING PROGRAM AT  
THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1994

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in Electronic Product Development**

by  
**Thomas E. Abell**

Submitted to the Department of Materials Science and Engineering  
and to the Sloan School of Management  
in partial fulfillment of the requirements for the degrees of  
Master of Science in Materials Science and Engineering and  
Master of Science in Management

**ABSTRACT**

Product development process improvement, especially with the goal of decreasing cycle time, is recognized by many companies as a key strategic objective. Improved product development processes allow companies to more quickly respond to customer needs, to more effectively incorporate new technologies, and to improve product functionality, quality and costs.

This thesis describes an effort to evaluate a electronic product development process using a methodology called Design Structure Matrix (DSM). This evaluation focuses on the prototyping phase of product development and includes a DSM-based mapping of the product development process and recommendations for process improvements. The thesis also describes an improvement effort in the linkage between the design and manufacturing functions in product development. The thesis concludes with a discussion of product development benchmarking, which includes a proposed benchmarking methodology and an example benchmarking study between two electronics companies.



## **ACKNOWLEDGMENTS**

This thesis could not have been completed without the help of many people. The LFM Program provided the environment and resources that allowed all the contributors to get involved in this multi-disciplinary effort.

My academic advisors, Daniel Whitney and Steven Eppinger, proved to be ideal advisors for this project. They are both very interested in product development, and they both added a wide variety of expertise. Steve and Dan took the time to visit my internship site several times, and we otherwise maintained frequent communication via electronic mail.

There are many people at the company where my internship took place and MIT who helped make this work possible. I am very thankful to all who assisted me and supported my efforts in this project.

The author wishes to acknowledge MIT's Leaders for Manufacturing Program for its support of this work.

The author also wishes to note that the host company significantly edited the contents of this thesis document before releasing it for final publication.



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## 1.0 INTRODUCTION

### The Strategic Importance of Product Development

In recent years, product development has become increasingly recognized as a critical area of competitive advantage by many companies. Technology is evolving at such an increasing pace that product development teams are having trouble simply keeping up. Companies are having to look more closely at product life cycle issues as technological change reduces the market viability of many products from years to months. Customer satisfaction is now recognized as a key long-term success factor for most companies, so product development efforts must get better at identifying customer needs and must reduce the time it takes to respond to changes in customer needs. It is becoming more widely believed that reducing product development time will lower overall product development costs even though more resources may be needed during the development cycle.

As emphasized in recent product development literature, continuously-shrinking product life cycles are making time-to-market a much more important success factor for today's product development activities. High-tech products often have market lives that are less than a year. These products often decline in price very quickly after they are introduced. Short market lifetimes and rapid price declines greatly increase the penalty of delays in product development projects. Being late by as little as a month can reduce a product's lifetime profitability significantly.

### Goals of the Thesis Project

This thesis represents a joint effort between MIT and a major electronics company through MIT's Leader's for Manufacturing Program. The majority of the work took place during a seven-month internship at the company. The project was originally conceived as an opportunity to improve the product development process at the company in one of its divisions. Like many joint projects between academia and industry, the thesis had to satisfy both the academic requirements of MIT and the need by the company that the

effort yield a value-added contribution to the company. With this in mind, the project was initiated with two major components. One was performing a broad evaluation of the development process looking for major improvement opportunities. The other was implementing a well-defined improvement to one specific area of the product development process.

### Organization of the Thesis Document

This thesis is organized into major sections representing the major components of the project. These are mapping and evaluation of the product development process and development of a product development process benchmarking study.

Mapping and evaluation of the development process is documented in Chapters 2 and 3. Chapter 2 covers the process overview and contains a detailed description of the important process steps. The Chapter also lays out two example development projects to give some understanding of how a development effort evolves. Chapter 2 concludes with a description of the design structure matrix representation of the product development process. A summary of the design structure methodology is included as background.

Chapter 3 contains the product development process evaluation. This evaluation focuses on the prototyping phase of the product development cycle. The design structure matrix representation provides a structural framework for evaluating many of the improvement opportunities.

Chapter 4 describes the specific product development process improvement effort of enhancing the connection between design and manufacturing.

Chapter 5 describes a product development process benchmarking effort.

Chapter 6 contains the final conclusions and recommendations for future research. The document is then concluded with a bibliography in Chapter 7.

## **2.0 PRODUCT DEVELOPMENT PROCESS SUMMARY**

This chapter provides an overview of the product development process and contains a detailed description of the important process steps. A summary of the design structure methodology is included as background.

This chapter focuses primarily on the engineering tasks required to develop products instead of marketing and financial processes. Some background discussion is given, however, to the non-engineering functions. Similarly, this effort did not attempt to evaluate the organizational structure of the product development community at the company. Although this is a heavily researched topic in the product development literature, our team did not believe that this project should begin with such a wide scope. Finally, the method of selecting different development projects across the continuum of market opportunities was not studied in this thesis. This area, commonly referred to as the "development funnel", is quite interesting from both academic and practical points of view, but it is too sensitive to the company to be a prime research opportunity.

### **2.1 BACKGROUND**

#### **Electronic products**

The subject company designs, manufactures and markets electronic products. The electronic product is basically a set of components enclosed inside a plastic housing. The most important components are the printed circuit boards.

The subject company develops electronic products that are sold in markets throughout the world. There are very different technologies, regulations, and market forces throughout the world. The market for selling these electronic products also has basic structural differences across different countries

### Company Product Development Structure

Because there is so much variety in the worldwide product requirements of electronic products, the scope and scale of different electronic product product development projects will also vary considerably. An electronic product product development project can be anything from changing a few components on a printed circuit board to designing an entire new product using a new technology.

There are six major constituencies in a typical product development effort at the company. These are electrical design, mechanical design, manufacturing, software development, marketing, and industrial design. An electrical design team has the responsibility to design most of the electronic and operational elements of the product. This includes selecting electronic components, developing circuit schematics, and laying out components on printed circuit boards.

A mechanical design team has the responsibility to develop all the mechanical components like housings.

The manufacturing team is responsible for making sure that the new product can be manufactured. The team members usually work in the factory where the product will be assembled. A manufacturing team usually consists of one to five people who typically share development responsibilities with current-model manufacturing tasks.

Software development is responsible for writing all of the on-board software for new product designs.

Marketing is responsible for gathering customer requirements and determining the features that will go into each product. They also forecast sales figures, coordinate advertising plans, and develop product packaging.

Industrial design is a relatively autonomous group that specifies the aesthetic look and feel of new products. They get involved in the earliest stages of product development, exploring product concepts before engineering resources are committed. Industrial

designers develop drawings and renderings for exploring various product concepts, and they build styling models of the most promising concepts. Industrial designers must work most closely with mechanical designers, who must engineer the aesthetic form as plastic housings. The electrical team must also get involved, though, to ensure that the electrical components can be packaged inside the specified form.

### Company Product Development Process Observations

In the development projects studied in this research effort, the product development process is characterized by hardware-focused prototype iteration.

Some of the difficulties experienced by product development teams are as follows: Program inception is sometimes unclear, leaving engineering teams without clearly defined objectives. Few product development process metrics are tracked, so quantification of improvement opportunities is difficult. Programs are often redirected in response to changing market needs. This sometimes forces engineering teams to revise significant amounts of work.

As one would expect, many of the strengths of the development process at the company are closely related to the weaknesses. An advantage of the company is the flexibility of product development efforts. Engineering teams are able to quickly respond to new challenges and can quickly implement new technologies.

Other advantages to the product development process at the company are close supplier interaction, technology-driven development efforts.

## 2.2 DESCRIPTION OF PROCESS STEPS

This section describes the major steps in the development process of a electronic product at the company. The description is based on two example programs which are covered in the following section. The steps presented here represent a generic ground-up development project. Many projects that are smaller in scope would not require certain

steps, while some projects that include major new technologies would require additional process steps to handle the added complexity.

The important steps of the development process are broken down into five major areas. These are preprogram development, mechanical development, electrical development, software development, and product launch. Preprogram development is the initial phase of a project when overall targets are specified for things like cost, functionality, and size. Mechanical, electrical and software development occur simultaneously. Mechanical development is the set of steps required to identify and design all of the mechanical components of the new product. Electrical development is the set of steps required to implement the hardware functionality of the product. Software development is the process of specifying, creating and, testing the software features of the product. Product launch is the period when the design is finalized and transferred to manufacturing for volume production.

### 2.2.1 Preprogram

The preprogram portion of the product development process is called preprogram because much of it occurs before the development project has been formally approved. Preprogram work, of course, flows directly into later steps, but its main focus is to define the new product at a detailed enough level for management to approve the program and allocate resources. The steps are listed below and are briefly described.

- Develop targets for the physical package.

The major elements of a product's physical package are height, width, thickness, and weight. The industrial design department is responsible for the aesthetic styling of the product. They develop physical models of design alternatives. The product's overall size is estimated by summing the sizes of the major components.

- Identify major board components

Boards and electronic components make up a large percentage of the cost of the product, so much of the preprogram development involves selecting specific electronic components. These selections drive most of the important functional attributes of the product.

- Identify major mechanical attributes:

The materials and technologies that comprise the mechanical components of electronic products change continuously, so every new project must re-evaluate major decisions. Different types of plastics are constantly being pursued that better satisfy requirements for durability, moldability, cost, and strength. New materials for other components are continuously being introduced by various suppliers, and new programs must be aware of the latest technologies.

- Program Initiation

Program initiation is the set of activities that move a development effort from an initial study phase into a committed program. This commitment occurs through the dedication of resources and the approval of documents.

### 2.2.2 Mechanical Development

- Get Industrial Design specification of Styling Model

The styling model is the aesthetically designed outside shape of the product. The industrial design department provides a physical model of the product.

- Solid Model of Styling Model

A mechanical CAD package is used to develop a solid model representation of the styling model.

- Stereo Lithography Model of Styling Model

Stereo Lithography (SLA) is a method of producing a plastic model from a CAD representation of a part. This model is used to verify the accuracy of the CAD database, and it is an easy way to get a physical representation of the current design.

- Approval of Styling Model

The styling model must be formally approved after every significant change.

- Choose Purchased Components

Purchased components are generally handled by mechanical engineering. Electrical engineering must specify the electronic characteristic of these components.

- Choose Materials

Materials used in products are constantly evolving. New materials and molding techniques are often proposed by vendors or found in trade magazines. The plastics and molding industry is fragmented with many small suppliers that have unique capabilities. It is critical to have an experienced mechanical engineering team to understand the capabilities of the many different vendors.

- Determine Necessary Housing Strength

There is a need to minimize weight and material cost while at the same time maximizing the strength, durability, and manufacturing feasibility of the product. Wall thicknesses, for example, are very important for injection-molded parts, which includes most housing components. This process starts at the very beginning of the program, and it continuously evolves as materials are selected and as components are defined.



- Build Mechanical CAD Models of Major Components

As the definition of individual components becomes more concrete, CAD models are built and updated.

- Select Attachment Methods

Attachment methods are the things like screws, slots, and tabs that provide a means of attaching all of the components. After the housing components are defined, the attachments between them must be defined and added to the CAD models of the components.

- Check Component Fits in CAD

Solid models of components allow the designers to check that package requirements are being met. This is done by bringing together in the computer each of the individual component models, and checking the distances between component boundaries.

- Develop Assembly Procedures

As the mechanical design of the product evolves, the mechanical design and manufacturing teams define the assembly steps that will be used in the factory to assemble the product. This process evolves through design changes and prototype builds.

- Select Prototype Tool Vendor

Prototype tools of plastic components are usually made with "soft" materials like aluminum and usually contain only one part cavity. These tools are made to check the moldability of the design and to generate parts for prototype products. The prototype tool vendor is selected usually by engineering based on the particular technological needs of the program and on the responsiveness of the vendor.

- Design Prototype Mold

Using the CAD component database, the vendor must design and build a prototype mold. This is done in conjunction with the mechanical engineering team at the company.

- Moldflow analysis of mold

Moldflow is a type of finite element analysis that simulates the process of filling the mold. This can be used to evaluate different gating configurations at various temperatures and pressures to optimize the mold design.

- Order prototype tools

These original prototype tools evolve over time and are eventually used to make production material during the early product launch phase.

- Build Prototypes

Prototype housings and components are combined with prototype boards so the entire product design can be evaluated.

- Order Production Tools

After the prototype tools have reached a high enough level of quality, production tools can be ordered. The design of production tools is based on prototype tools, except that they are made of hardened steel instead of aluminum which makes them more durable. Production molds also have automatically-actuated components for volume production.

### 2.2.3 Electrical Development

- Preprogram Targets

The electrical development effort is begun during the preprogram phase.

- Agree on PWB Design Rules.

PWB design rules are standards for board designs that must be worked out between design and manufacturing. In the company, each factory develops its own specific set of design rules for each new program based on the current state of technology in the factory.

- Develop and Review Circuit Block Diagram

The block diagram is the basic outline of circuit functionality.

- Specify Solder Geometries (Padstacks) for Surface-Mounted Components

A critical manufacturing parameter for electronic components is the shape of the solder joints that connect the component to the board.

- Certify New Components and Vendors

New components must go through a formal certification process, and new vendors must be approved by the purchasing department.

- Create Schematics

From the block diagrams and the bench prototypes, the overall schematics for the various circuit sections are created.

- Constrain Major Component Locations

This process is started during preprogram development, where component locations must be estimated to determine the overall package dimensions. The process continues to evolve to the very last prototypes because performance optimization typically requires at least minor and sometimes significant rearranging of components.

- Approve Schematics

The electrical design team conducts a review of the schematic design.

- Specify Test Points and Parameters for Board Test

During regular production, all boards are tested in the factory after component assembly. These tests are done on the manufacturing line with automated equipment that must know the location of all test points and parameters to be tested.

- Layout Board(s)

The completed schematic is transferred to a board designer who lays out the components and traces.

- Order Prototype Boards and Solder Stencils

Once the board designer has finished a layout, the design is sent to board and solder stencil vendors. Good prototype vendors can supply boards in a few days. Orders from production vendors can take a week or more.

- Transfer Component Layout to Manufacturing

PWB design information must be transferred to manufacturing, where the prototype boards will be populated.

- Assemble Prototype Boards

Prototype boards are run in the factory when production capacity is available.

- Test Basic Analog/Logic Functionality

Prototype boards are first tested for basic functionality at a test bench in the engineering department.

- Specify Parameters For System Test

System test is the last step in manufacturing where the completed product is tested for complete system functionality.

#### - Assemble Boards Into Housings

When prototype boards and housings and necessary components are available, prototype products are assembled. Early models simply serve as basic checks for component fits.

#### 2.2.4 Software Development

The example programs used for developing this list of process steps did not require significant software redesigns. Although software is becoming a more and more important part of the development process, this thesis focuses mainly on the hardware development steps. The following steps describing the software process should, therefore, be interpreted as the minimum software effort required for the development of a new product.

#### - Determine Code Requirements

Software requirements are usually based on marketing requirements for functionality.

#### - Debug Completed Code

The software group performs structured quality assurance procedures before releasing new code. This is first performed as a simulation within the computer system where code is written.

#### - Test Code in Prototype Products

When prototype hardware is available, software is tested in the field.

#### 2.2.5. Product Testing and Manufacturing Launch

This is the final stage of the product development process, where final bugs are worked out of the design and volume manufacturing begins.

- Product Reliability Testing (PRT)

This is the key quality assurance step for new products. PRT is a standardized procedure that subjects products to a variety of extreme environmental and operational conditions.

- Functionality/Vibration/Drop/Dust/Use Tests

Additional testing and verification is performed as needed. This can be to address specific issues that must be resolved more quickly than the PRT procedure allows or to address problems that are beyond the scope of PRT.

- Prototype Authorization/Ship Authorization/Ship Acceptance

These are a group of standardized quality assurance procedures that each product program is supposed to satisfy at specific points in the product development process.

## 2.3 TWO EXAMPLE DEVELOPMENT PROJECTS

This section provides an overview of two example development efforts at the company. The descriptions of these two programs have been made generic to avoid revealing any confidential data. The programs, referred to as Project A and Project B, are good examples because they are both relatively ground-up designs. Although Project B contains more new technology than Project A, they both have new housings and new boards. Both programs, however, used primarily existing technologies, which limited the size of software development efforts.

The two programs were also used as the background for the development process mapping described in this chapter. Interviews of personnel from both teams provided most of the data used to lay out the development process.

### 2.3.1 Project A

Project A was a completely new design attempting to push the limits in a few functional parameters. The main drivers of the program were the technical challenges of meeting the functional targets. A major feature of the timeline is the fact that the program was redirected. The product's styling was almost completely revised, so most of the mechanical design work had to be restarted. Because of this, the board development effort did not get into a regular prototyping schedule much later in the program. Later, the failure of a major purchased component to make its package targets required another significant mechanical redesign. This example illustrates how difficult it is to meet program schedules when project direction is significantly changed.

### 2.3.2 Project B

Project B was a complete redesign, with lower the manufacturing costs and improved functionality over an existing product. The main observation feature of the timeline is the standard progression of board prototypes. These occurred on a relatively consistent schedule. Regularly scheduled prototype builds like these are often called milestone prototypes because progress is measured by the evolution of the performance of successive prototypes.

Prototypes are built at regularly-scheduled intervals until the end of the project when their rate accelerates. This strategy works well to maximize the manufacturing involvement in the development effort. It does, however, create a large workload for engineers who must handle prototype material for every build.

## 2.4 PROTOTYPE ITERATION AND THE DESIGN STRUCTURE MATRIX REPRESENTATION

### 2.4.1 Prototype Iteration As Focus of Development Effort

As seen in the example programs, prototype iteration is the most significant activity in the electronic product development process. Prototype iteration begins very early in the process and continues until the product is ready to ship. Passing the product reliability testing is the most important criterion in deciding whether a product can ship, and all except the earliest prototypes are tested. Prototypes provide the primary means of communication on development issues, and they act as milestones for program scheduling and progress reporting.

The large number and high frequency of prototype iterations illustrates how the product definition process evolves over time. The design, therefore, gradually evolves across several fronts through the prototyping process.

Every prototype generation will contain at least some minor change to the board layout. Changes to other major components usually take significantly longer to turn around, so revisions do not occur in every prototype iteration. Because of the different lengths of time required to revise different types of components, the prototyping process can be viewed as a series of nested loops.

Because of the significance of prototyping, we decided to use that as the basis for our evaluation of the electronic product development process. Most of the product development tasks described in Section 2.2 fall somewhere in the prototyping process. We chose to organize the tasks into a model called a Design Structure Matrix (DSM). The DSM, described in the next section, is an ideal representation for highly iterative processes like prototyping.



### 2.4.2 Background on Design Structure Matrix

Many techniques exist for modeling product development activities. Flow charts can be used to show the relationships between development tasks, and Gantt charts are often used to estimate the length of each activity and to expose critical path tasks. The Design Structure Matrix (DSM) model was conceived by Steward [1981] and has been the subject of significant work by Eppinger et. al. [1990 - 1993]

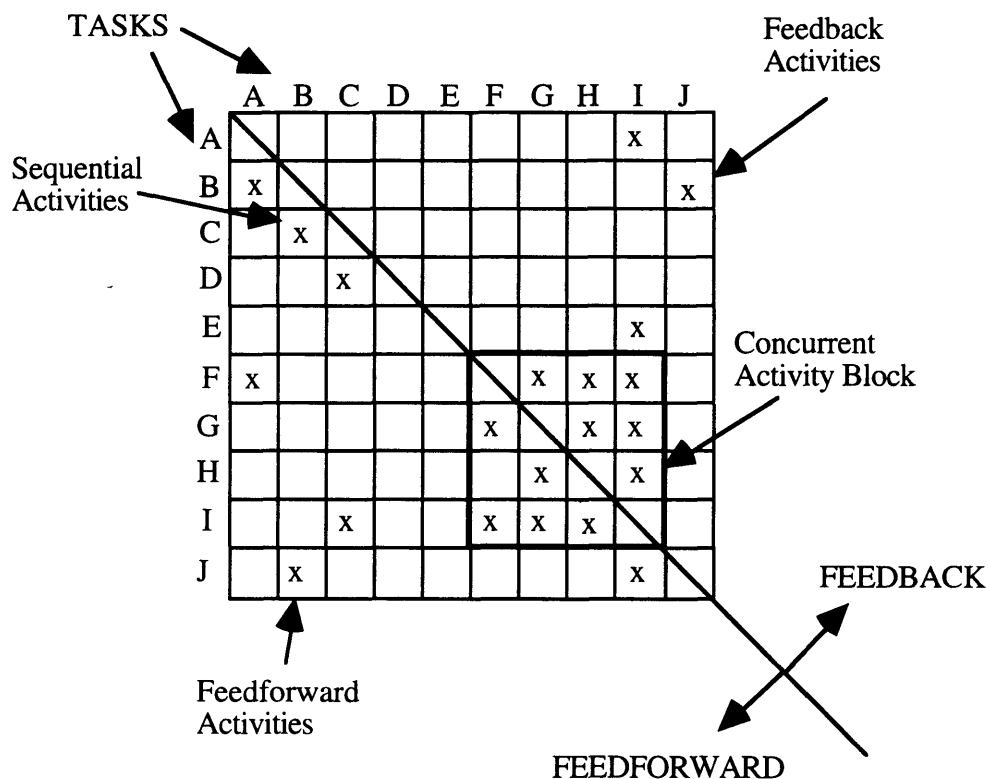


Figure 2.1. Example Design Structure Matrix.

Figure 2.1, above, shows an example Design Structure Matrix. The rows and columns represent product development tasks, usually arranged in roughly chronological order. So in the figure, task A could be a product initiation task, while task J could be a later task like manufacturing release. The elements in the matrix, designated as x's,

represent interaction between the different activities. So for example, an x in the first column in row B indicates that the task B is dependent on task A. The diagonal elements of the matrix represent the special case of tasks influencing themselves. Because the tasks are arranged chronologically, the elements below the diagonal show feed forward causality, and the tasks above the diagonal represent feedback loops. By looking down column A, one can see that activity A feeds into the down stream tasks B and F. Similarly, looking down column J shows that activity J feeds back into the upstream activity B.

By representing feedback and feed forward as matrix elements instead of pointers in a flowchart, the DSM is much more effective in illustrating the complex interactions between tasks in typical product development processes. The DSM is also very effective in illustrating the flow of development activities. Groups of elements just below the diagonal represent sequential tasks that flow one into the next, while blocks of elements around the diagonal represent highly interactive groups of activities that usually must be done concurrently.

DSM provides an effective method to communicate the activities and structure of product development processes. It can also be used to show how changing the order of process steps will influence iteration. The work of Eppinger et. al. [1990 - 1993] has demonstrated ways to extend the DSM methodology to attempt to optimize the structure of development processes. If the matrix elements indicate some degree of dependency between tasks, one can use the matrix to identify constraints in the development process. Black, et. al. [1990] illustrates this in a brake design process, where two major themes were found, one for minimizing the weight of the overall system and one for maximizing the heat dissipation of the system.

By adding additional information about the length of time required for each step in the development process, the DSM can be used to optimize the ordering of tasks in the development process for minimum expected cycle time. Research efforts continue to find

more uses for the DSM methodology, and eventually the DSM may be useful for real-time product development scheduling or for evaluating project alternatives for risk analysis.

#### 2.4.3 Design Structure Matrix Representation of Product Development Process

Figure 2.2 shows the DSM representation of the electronic product development process. The DSM is partitioned into four major blocks. These correspond to the major development areas outlined in Section 2.2, except that software development has been omitted from the DSM. The first DSM block is preprogram development. The activities in this block are highly concurrent, indicating the high degree of interdependence between all of the tasks. These tasks form the basic program assumptions for a new development effort.

The vertical column below the Preprogram block illustrates how the preprogram activities feed forward into mechanical, electrical, and manufacturing release activities. Similarly, the horizontal row to the right of the preprogram block shows how other activities feed into preprogram definition. For example, agreeing on Manufacturing design rules, activity 30, feeds into several preprogram tasks. This illustrates the fact that a significant amount of engineering work must be performed during the preprogram stage of a project.

The electrical steps in the DSM are arranged separately from the mechanical steps, even though they occur simultaneously. This arrangement highlights the interactions between the electrical and mechanical development efforts. These interactions are the active matrix elements in the off-diagonal blocks in the upper right and lower left areas of the DSM.

The block labeled Mechanical Self-Interaction shows the interaction among all of the mechanical engineering steps. These are activities that are self-contained within the mechanical engineering team. For example, activity 26, testing prototype parts, feeds back into several activities like designing molds and selecting materials.

The block labeled Electrical Self-Interaction shows the interaction among all of the electrical engineering steps, which are self-contained within the electrical engineering team. For example, activities 43 and 44 involve testing basic functionality and performance, respectively. These activities feed back into several electrical design steps like creating schematics and laying out components.

The blocks labeled Mechanical Inputs to Electrical Design and Electrical Inputs to Mechanical Design show the major interactions between electrical and mechanical design. Because electrical and mechanical design occur simultaneously, the interactions do not necessarily imply feed forward or feedback as normally indicated by the position above or below the diagonal in the DSM. From mechanical engineering, some major interactions with electrical design are activities 11 and 15, choosing purchased components and specifying housing configurations. The housing configuration is also important for electrical design because it influences the board outline and constrains the locations of electrical components. From electrical engineering, some important inputs to mechanical design are activities 29 and 37, which are specifying the board outline and laying out the board. The board outline has a significant influence on the definition of housing components because the housing must hold the board in place. The location of large electronic components on a board influences the design of the housing because housing features must not interfere with the components.

The final block of activities is the set of program completion tasks. Task 47 is product reliability testing. The appearance of this activity at several points above the diagonal illustrates how it is one of the primary feedback mechanisms of the prototyping process. Overall, the DSM is very effective in showing the nature of prototyping in the development process. Within the four major groups, tasks are generally arranged chronologically, so the matrix elements illustrate possible feedback and feed forward causality. The large number of off-diagonal tasks shows that a single prototype iteration can involve a great number of the tasks in the DSM.



		Electronic Product Development Process Steps																					
		Preprogram								Mechanical Development													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Preprogram	1 Product Concept	1	x	x	x	x			x														
	2 Identify technologies to be used	x	2	x	x	x	x		x								x					x	
	3 Cost, volume, quality targets	x	x	3	x	x		x	x			x					x					x	
	4 Schedule	x	x	x	4	x	x	x				x				x							
	5 Contract Book Signoff	x	x	x	x	5			x								x					x	
	6 Engineering Resources Committed		x			x	x	6															
	7 Document Functionality Requirements	x						x	7	x			x										
	8 Styling model from ID	x	x							8													
Mechanical Development	9 Solid model of styling model								x	9	Mechanical Self-Interaction												
	10 Approval of styling model									10							x						
	11 Choose Purchased Mech Components		x	x	x			x		x	11						x			x			x
	12 Model Purchased Mech Components										x	12											
	13 Choose Housing Materials		x	x	x				x		x		13	x	x					x		x	x
	14 Test Materials (heat, scratch, wear, etc.)												x	14	x								
	15 Define Major Housing Components			x					x		x			x	15				x	x	x		x
	16 Estimate Material Cost										x		x		x	16							
	17 Build Mech. CAD model of Major Components									x	x	x			x		17	x					
	18 Select Attachment Methods		x	x					x		x		x	x	x				18			x	
	19 Check component fits in Mech. CAD										x	x							x	19			
	20 Assembly development			x		x					x		x		x				x	x		20	
	21 Select Proto Tool Vendor			x	x								x										21
	22 Design Proto mold													x								x	22
	23 Moldflow analysis of mold													x									x
	24 Order proto tools					x																x	x
25 Order Proto parts					x																	x	
26 Test Prototype parts																							
27 Select Production Tool Vendor(s)			x	x										x							x	x	
28 Certify Production Tools																							
Electrical Development	29 Board Outline								x								x						
	30 Agree on mfg design rules		x	x		x			x														
	31 Develop/review block diagram					x																	
	32 Create Schematics								x														
	33 Certify new components and vendors																						
	34 Constrain major component locations								x		x					x							
	35 Approve schematics																						
	36 Specify board test points and parameters																						
	37 Layout board(s)											x					x					x	
	38 Select production board vendor			x	x																		
	39 Order proto boards/masks				x																		
	40 Transfer board layout to mfg																						
	41 Generate placement programs																						
	42 Build proto boards					x															x		x
	43 Test basic functionality																						
	44 Performance Testing																						
	45 Specify system test parameters																						
Manufacturing Release	46 Assemble boards into products																						x
	47 Product Reliability Testing			x					x														
	48 Prototype certification			x					x														
	49 Complete documents/packaging								x														
	50 Lead customer shipments					x																	
	51 Field Testing (Beta)																						
	52 Ship Acceptance									x													
	53 Volume Production																						
	54 Ship Authorization								x														

						Electrical Development																	Manufacturing Release									
23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
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### **3.0 RECOMMENDATIONS FOR PROCESS IMPROVEMENT USING THE DESIGN STRUCTURE MATRIX METHODOLOGY**

This chapter describes ways to improve the electronic product development process. The design structure matrix process representation provides a background and model for evaluating different process improvement opportunities. Section 3.1 summarizes the different improvement opportunities. Section 3.2 describes the importance of metrics in prioritizing and evaluating continuous-improvement processes. Section 3.3 covers opportunities in streamlining the prototyping process, and Section 3.4 describes the potential impact of various computer-aided engineering tools.

#### **3.1 METRICS**

Establishment of a comprehensive set of metrics is a necessary first step if a company wants to be able to objectively identify and evaluate improvement opportunities. In the past, product development improvements at the company have occurred in a "grass roots" manner. Usually a small group of individuals takes on the responsibility for selling a change to the rest of the organization through some kind of pilot project. This method worked extremely well when the company was small, but as the company has grown, these types of improvement efforts have become harder to manage.

Establishing and tracking product development metrics does not explicitly improve product development performance. In fact, tracking metrics takes time and thus may initially reduce product development productivity. The benefit, however, is that tracking metrics provides necessary data to evaluate and justify improvement opportunities. At the company, relatively few development metrics are tracked regularly. Those that are, like prototype release dates and product cost and weight, are used for individual project management rather than for learning across projects. The tracking systems are, therefore, specific to the different engineering departments and managers depending on individual preferences.

Metrics can provide the objective data that are needed to create change in large organizations. Metrics will not work without the wide organizational support that is necessary for implementing a comprehensive and well understood measurement system. Once a common measurement system is established, not only will improvements be easier to justify, but planning and forecasting will become more accurate. Once improvements are implemented, metrics will also allow for more accurate measurement of results.

The design structure matrix is the ideal starting point in an effort to establish product development process metrics. The DSM illustrates how important product data is stored and when it gets handed off between activities. A good set of metrics should have the following characteristics:

1. Track the evolution of major sources of product data.
2. Follow the transferring of product data between activities.
3. Measure the time spent on different activities by product development personnel.
4. Track sources of development process iteration and measure their frequency.
5. Quantify defect opportunities in each activity.
6. Minimize time spent documenting, or, if possible, automate metric tracking.

The evolution and movement of product data can be found in the development activities in the DSM. A comprehensive set of metrics should track each of the major constituents of product data. The time and nature of every change to this information should be recorded along with a quantification of the resources that were required to make the change. For computer-based product data elements like PWB layouts, schematics, and CAD geometry models, much of this data collection can be performed automatically.

In addition to tracking the changes to product data, a comprehensive measurement system should follow product data through hand-offs between activities. The date and time of each product data transfer should be recorded as well as an estimate of the time required to make the transfer. Many of these processes can also be tracked automatically. It is important that the flows of product data are well understood. The DSM shows how major activities are interconnected. This should be supported with measurements of the time

required to make product data transitions and illustrations of any errors that can be introduced at each step.

Metrics should also measure the time spent on different activities by development team members. This will allow easier quantification of improvement opportunities. Major sources of iteration, like PWB layouts and mold designs should also be measured. The date along with some indication of the severity of each change should be recorded. This will provide a better understanding of the development process, which would help to enable the restructuring of the process for lower cycle times. A quantification of defect opportunities should also be part of a system of metrics. Evaluating processes and predicting where major errors can occur will make the development teams more aware of possible problems to be avoided.

### 3.2 PROTOTYPE PROCESS IMPROVEMENT

#### Improved/Automated Problem Tracking

Prototyping can in some ways be viewed as a process for discovering, investigating, and resolving design problems. These problems are communicated through various engineering documents and are discussed in regularly-scheduled engineering meetings.

Developing a standardized and automatic system for tracking and updating engineering problems would make the data available for improvement efforts. If such a system was visible to every member of the development community, it would also improve the communication among the development team.

#### Bill of Material Management

The bill of materials is basically the list of all components that will comprise a new product. This consists of the PWB, all the electrical components, wires and connectors,

plastic housing parts, etc. In the DSM for electronic product development, activities 16, 20, and 47 cover the bill of materials management.

The current system for managing the bill of materials for development projects is similar to the system for tracking engineering problems. The bill of materials exists in several forms. Some of these are: 1. Spreadsheet in the manager's computer, 2. Circuit Schematics, 3. PWB layout files.

Generally, the electrical and mechanical development managers are responsible for managing the bill of materials for their respective areas until the product is ready for engineering release. There is no formal mechanism for making sure that the current bill of material is updated across all the different activities. When an engineer adds or deletes a part from a schematic, it takes time for this information to filter down into the PWB layout and into material control.

#### Prototype Material Tracking

The responsibility for handling prototype material is spread between development engineering and purchasing. The material control system for ongoing production is not well suited for prototype material. Entering new components into the system is slow and cumbersome, and the system does not handle revisions to existing components well.

Until the new product is ready for manufacturing release, most of the responsibility for ordering prototype material is handled by the development engineers who are designing the parts. The engineers must issue purchase orders for prototype parts before each prototype build. An electronic system for generating, approving, and tracking purchase orders could, therefore, save over a significant amount of engineering time during each prototype cycle if a major program.

#### Improved Contract Book and Product Requirements Document

The contract book and product requirements (PRD) document are major products of the preprogram phase of a development project. For example, project A in the previous

chapter never had a signed contract book, while the contract book for project B was never updated after its initial signoff. According to Smith and Reinertsen [1991], this is a common problem in development efforts. Organizational dynamics during the early stages of development generally impede efforts to generate detailed product specifications.

Preprogram development is a period of rapid design evolution and great uncertainty. It is also the time when major players in the development community negotiate over responsibilities and functional targets. These negotiations are often difficult to resolve until significant design investigations are performed. Therefore the involved constituencies may not agree to properly document important design issues.

### Restructured Prototype Process

The current prototyping strategy used at the company is decided mainly by the development managers responsible for each program. Usually either the mechanical manager or the electrical manager will take on the job of scheduling prototype builds and organizing development meetings.

Because there are typically several prototype builds, the evolution of the product design occurs gradually across each prototype iteration. Examining engineering problem lists and prototype reports over an entire program shows that there are some major trends in the evolution of typical programs.

As the company's business becomes more mature, its product development community finds itself developing more and more products. Many of these products follow the same basic development steps, and it may become desirable to standardize parts of the development process so that best practices can be applied quickly throughout the organization. This strategy would also permit frequent problems to be identified more easily and provides a common format for communicating problems into future development projects.

One possible way to standardize the development process is to create a structured prototyping methodology. This technique has been used with great success in the automotive industry, where development processes have remained stable for many years. Wheelwright and Clark [1992] address the issue of prototyping strategies, and they emphasize the importance of matching prototyping strategies with types of development efforts. They list three categories of development projects and suggest general prototyping strategies for each. The three categories are **technology breakthrough** projects where major new technologies are introduced, **new platform** projects where a product is redesigned from the ground up without significant new technology, and **incremental** projects where basic revisions are made to existing platforms. Prototyping for technical breakthrough projects requires a very fast and flexible engineering approach to deal with the expected uncertainties of new technology. Incremental projects, on the other hand, require manufacturing-oriented prototyping to smooth the manufacturing release process. For new platform projects, a process called periodic prototyping is suggested which focuses on system integration. The idea is to focus each stage of prototypes on specific system issues instead of trying to solve the entire problem in every iteration.

The company develops products that fall into each of the three categories. The example projects A and B, from which the design structure matrix was developed, fall into the new platform category. A new structured prototyping methodology for this type of development project would have to be planned by senior members of the development community around the available product development tools. The development community is currently evaluating several different simulation and analysis tools. These tools must become more commonly used and their capabilities better understood before a structured prototype process like this could be implemented. Combining the periodic prototyping idea with the current trends in the company's prototype evolution, however, could eventually yield a new development structure.

### 3.3 COMPUTER-AIDED ENGINEERING TOOLS

During recent years, computer-aided engineering tools have been developed for a great number of special engineering problems. This section describes how some of these can be used to improve the process of developing electronic products. Some of these tools are already being used in pilot projects or on an as-needed basis in development programs at the company.

#### Heat Transfer Analysis

Some of the electrical components in an electronic product generate significant amounts of heat. This heat must be dissipated without thermally damaging internal components. Heat dissipation problems are usually discovered through physical prototypes. When a thermal problem is found, it can be solved by either relocating the "hot" component or adding a thermal barrier to redirect the flow of heat.

Thermal analysis can be used to reduce the chance of design delays due to thermal problems. Most thermal analysis techniques involve finite element (FEA) modeling of all of the major components. By including heat generation rates and thermal material properties, it is possible to calculate the operating temperature of the product under different conditions. This process can allow development engineers to test component configurations for thermal problems before any board layouts or housing prototypes are developed.

#### Durability Analysis

Durability is a major cause of prototype iteration during the later stages of product development. Product reliability testing typically brings up specific durability issues, like corners breaking in drop tests or housing fatigue over the product life. These failures are impossible to predict with pre-production prototypes that often use non-representative materials. These problems are typically found after tooling for housing components is finished. Soft tools can catch many of these problems, but the mold actuation and the

molding temperatures and pressures are often different with production tools, yielding unpredictable differences in component properties. Changes to this tooling takes a long time to turn around and can cause weeks of delay at the very end of a product program.

Using analytical tools to minimize these problems represents a significant cycle-time reduction opportunity. Two major types of finite-element analysis can be applied to these problems: stress analysis and vibration analysis. Stress analysis can be used to evaluate the overall stiffness and strength of a product. It is important that the product feels solid in the hands of the customer, and overall durability is also important. Both of these issues can be evaluated using FEA stress analysis. Stress analysis can also be used to evaluate the point stiffness at particular locations on the product.

Vibration analysis can be used to evaluate shock resistance and durability of products. Shock and impact failure are often governed by vibrational characteristics. Modal finite element analysis can be used to determine the natural frequencies of product housings. This can give insights into where components will break during impacts. These can be used to identify bending points on circuit boards that can cause component failures.

#### Mold Design Analysis

One of the longest lead-time items in the development of electronic products is the production molds for plastic housing components. It is, therefore, very important for minimizing development cycle time that this process is only done once during a given development project.

Using a finite-element method called moldflow, it is possible to evaluate the gating and molding parameters to optimize the filling of the mold and the material properties of the final product. The moldflow analysis can even begin before the final details of the part designs are complete. This can, therefore, significantly reduce the chance that iterations will be required on production molds.



### Circuit Simulation

Circuit simulation refers to the process of simulating the functionality of electronic circuits in a computer. This is a huge topic in both academic research and industrial performance, and it could easily consume this entire thesis. This section will simply summarize some of the major issues and opportunities associated with circuit simulation.

Circuit simulation can be used, like any analytical tool, to perform some design verification and optimization before physical prototypes are built. Simulations can be done for individual systems. They can also be performed on a system level. The real issue, however, is whether the time and effort required to develop circuit simulations will be offset by the benefits of the simulations.

Another problem with circuit simulation is that it requires computer models of the electronic components in the simulation. These models are not always available for new components, and there are several different standard types of models which are not universally supported by component vendors. Getting all of the necessary component models together and getting the development engineers trained on the intricacies of the simulation tools represents a large up-front cost which may be difficult to offset with tangible cycle time or productivity gains.

### Concurrent Electronic Design

The existing process of designing circuits and printed-circuit boards occurs in a serial manner. The turnaround time for prototypes could be reduced if new tools were used for concurrent engineering. This represents a significant opportunity to streamline the prototyping process in electronics design.

### 3.4 PRIORITIZING IMPROVEMENT OPPORTUNITIES

As described earlier, there are many reasons for companies to improve their product development processes. Some of these are: reducing cycle time, increasing quality, reducing costs, increasing productivity, and accelerating the rate of technological innovation. While all of these points are considered important at the company, the goals of cycle time improvement and engineering productivity improvement are particularly relevant. Cycle time must be reduced because the industry is rapidly evolving, and the company must introduce products more quickly to stay on top. Engineering productivity must be improved because the growth rate of the industry is straining the company's ability to hire and train new engineering talent.

#### 3.4.1 Prioritize Metrics and Process Automation

While all of the process improvement opportunities described in this chapter are potentially valuable, it is important to focus first on the opportunities that will provide tangible results and will enable the development process to achieve a more mature state. This means that priority should be placed on process metrics and process automation (which refers to automatic problem tracking, product data management, and prototype material management.) Metrics are required to justify and enable hard-to-implement solutions. Process automation can provide quick results by streamlining processes and reducing engineering workloads, but it can also simplify the task of identifying and tracking metrics.

#### 3.4.2 Cycle Time Reduction, Productivity Improvements, and Development Flexibility

During the process of developing the design structure matrix for electronic product development activities, many common issues were brought up by people in the development community. Some of these are: frequent program redefinition and a heavy prototype workload. The company has high-level objectives to get products to market

more quickly by reducing cycle time. At the same time, there is a desire to keep the organization as lean as possible as well as a tendency to make development projects as flexible as possible to react quickly to market changes.

The goals of reducing cycle time, maximizing project flexibility, and maintaining a lean organization can sometimes conflict. For example, engineers are sometimes pulled from one project to another to respond to a crisis. Working on the crisis can delay the original program. In this case, flexibility in assigning resources is traded against cycle time. Example project B in Chapter 2 experienced a major change in engineering direction during development. The need to respond to the latest market conditions was great enough to justify delaying the overall program. A common complaint about decreasing cycle time is that there are never enough resources to get programs completed on time. There is a limit to the speed that engineers can be hired and trained.

It is important to separate the goals of reducing cycle time and increasing engineering productivity. At a company like this one, however, where market growth is taxing engineering resources and where engineers often work on multiple programs, increasing engineering productivity will have a more direct impact on cycle time.

Different improvement opportunities can have different impacts on cycle time reduction, productivity improvement, and development flexibility. Automating common tasks like prototype material tracking and data management have large impacts on productivity but less impact on overall cycle time. Opportunities like formalizing the contract book and product requirements generation and restructuring the prototyping process can have significant impact on cycle time and productivity but can also limit the ability to change the direction of a development effort. Introducing more CAE tools to the development process can have a higher impact on cycle time than productivity because they can reduce the need for physical prototypes, but they create additional tasks for engineering personnel.

### 3.4.3 Prototypes: Physical versus Analytical and Many versus Few

There are four main reasons for building prototypes: communication, learning, verification, and milestoneing. Prototypes enhance communication by creating a common language. Prototypes facilitate learning through what-if scenarios. Many new issues often surface through prototypes that would otherwise never have been considered. Prototypes can verify that critical assumptions are correct and can uncover mistakes that occur in the development process. Prototypes can act as project milestones by demonstrating progress.

Prototypes can vary in scope from a simple component functionality test to a complete fully-functioning product. Styling models are prototypes of a product's form. Analytical models are prototypes of particular engineering parameters. Breadboarded circuits are prototypes of electrical functionality. Deciding what kind of prototypes to build and when they should be built should be done to maximize the rate of design evolution while minimizing the required costs, time, and development resources.

Analytical prototypes can provide knowledge only over a narrow range of design parameters. It is also more difficult to communicate the results of analytical prototypes because interpreting results often requires specialized technical skills. Analytical prototypes can, however, be easily modified to explore different design alternatives. Physical prototypes, which can be expensive and time-consuming to develop, have the advantage that they automatically incorporate natural variability. Multiple prototypes must be built, however, to evaluate the statistical variations in the design.

The timing of prototypes must also be driven by the need to maximize design evolution while minimizing cost, time, and resources. The trend in industry has been to reduce the number of physical prototypes while trying to increase the effectiveness of each. This does not mean, however, that fewer prototypes is always better. In an example described by Singh [1992], a team decided instead to increase the number and speed of prototype iterations in order to decrease overall development cycle time. Indeed, if it is

clear that physical prototypes are the fastest and cheapest way to evolve the design process, it may be better to streamline the prototyping process and increase its rate rather than slowing it down.



## **4.0 IMPROVING THE LINK BETWEEN PRINTED CIRCUIT BOARD DESIGN AND MANUFACTURING**

This chapter describes an effort to make a specific improvement to the product development process at the company where I interned.

### **4.1 BACKGROUND**

The printed circuit boards, referred to as PWBs (printed wiring boards) or simply boards, are the core component of most electronics products. The PWB provides the electrical connections between all of the electrical components of a product. PWBs are made of alternating laminated layers of metal and insulator material. Electronic components like resistors, capacitors, and integrated circuits (ICs) are assembled onto PWBs and then soldered into place. Modern electronic assembly facilities use high-speed automatic component placement machines to attach components onto PWBs. The process of attaching components to boards is often called populating. Usually two or more component placement machines are used to assemble components to each side of the PWB. So a single assembly line can contain several placement machines where each machine handles a small subset of the electronic components on a circuit board. Faster placement machines specialize in assembling small, commonly-used parts like resistors, while other machines specialize in placing large components that require greater accuracy.

PWBs are manufactured in groups of usually 2 to 4 boards. The group of boards is manufactured into what is called a panel. The exact size of a panel is determined by the requirements of the manufacturing line where the boards will be populated. After all the boards in a panel have been populated, they are separated from the panel so they can be individually assembled into product housings. Tooling holes in the panels provide fixturing locations for the component placement machines. Each placement machine has locator pins which mate with the tooling holes in the panel to precisely locate the panel's position with respect to the machine.

Most automatic electronic-assembly machines also have sophisticated vision systems which help the machine ensure the proper placement of electrical components. These vision systems can detect whether the correct component has been placed, and they can check that a component is in the correct angular position before placement. Because component placement is becoming an increasingly precise process, vision systems are also commonly used to fine-tune location data on the PWB. As the placement head moves across the board placing components, it loses accuracy in its locating ability. To correct this problem, locator marks called fiducials are placed on the board in particular locations. The vision system uses these fiducials to continuously check and update its location on the board. Some components need such extremely precise placement that a fiducial is located adjacent to the component on the board so the vision system can maintain the most precise location data possible.

Another important use of the vision system on component placement machines is to detect defective boards. All of the boards in each panel are tested before component assembly. There are usually several boards in each panel, and sometimes one or more of the boards in a panel is found to be defective. Any components that are placed on a defective board are essentially being wasted, so it is in the factory's best interest to have the component placement machine skip the defective boards. To accomplish this, panels contain marks, called block skips, which signal whether the corresponding board is defective. The block skip of a particular board is marked if that board is found to be defective in pre-assembly testing. The vision system of the component placement machine can then check the block skip and skip over a board if it is defective.

Because every electronics firm in the world must use and understand PWB technology, there are many standardized processes and technologies that are used throughout the industry. A few major computer-aided design tools are predominantly used to layout circuit designs, standard interfaces are used to communicate with board-



fabrication companies, and a few major vendors supply most of the automatic component placement machines to manufacturers throughout the industry.

Because so many of the interfaces and tools in the electronics industry are standardized, the PWB product development processes used by different companies throughout the industry are similar in overall structure.

The design concept sets targets for design parameters like functionality, cost, size, etc. With this information, design engineers create a schematic. The schematic contains information on which electronic components are used in the design and how those components are electrically connected. Once the schematic is finished, a PWB designer can layout all the layers of the board using a computer-aided design station. In addition to the layers of the PWB, the designer will create a pattern for solder stencils. Solder stencils, or solder masks allow solder to be applied to the appropriate areas of PWBs before electrical components are attached.

Usually both the solder stencils and the PWBs are manufactured by outside supplier companies. The PWB design existing in the CAD station also contains the identity and location of all the electronic components that will populate the PWB in the final product. This information is required for programming the automatic component placement machines. It must also be given to the material procurement organization so that the appropriate orders can be placed with component manufacturers. Electronic components are typically supplied to the factory in the form of reels. One reel can contain hundreds or thousands of components attached to a long strand of tape that is rolled onto the reel. These reels are mounted directly onto feeders on the component placement machines. Each machine can have over a hundred different feeders, and the machine controller associates each feeder with a particular component. The location of all the different feeders on the machine is called the machine setup.

Once the solder masks, unpopulated (or bare) boards, and necessary electronic components have been manufactured by the respective suppliers and shipped to the

assembly facility, PWB assembly can begin. Solder is applied to the boards at a solder station. After component placement machines are programmed, the boards are then populated, and the finished boards are ready for final assembly.

We chose the link between PWB layout and component placement programming as an improvement opportunity. This is a very significant internal communication process in the company's PWB development efforts because it is the primary connection between design and manufacturing.

#### 4.2 EXISTING PROCESS EVALUATION

Each of the different factories in the company operate relatively autonomously, and the process of transferring design data can vary from one factory to the next. Listed below is a summary of some typical process steps required for transferring PWB design data to manufacturing.

##### Process Summary

1. PWB Designer, after completing board layout, calls the responsible manufacturing engineer and gives the file name and location of the PWB design file in the CAD system.
2. Manufacturing engineer logs onto CAD system and runs a program to transfer a data file into a standard directory.
3. Manufacturing engineer logs onto another computer system and copies the file from the CAD system to the second system.

##### Problems and Issues with the Existing Process

1. The procedure takes significant amounts of a manufacturing engineer's time, even if there are no problems and if there are no new components.
2. Important files are not held under revision control, and file names are often arbitrary.
3. Boards and panels do not have a well-defined naming convention.

#### 4.3 DEFINITION AND IMPLEMENTATION OF IMPROVED SYSTEM

As outlined above, the existing system for transferring PWB designs to manufacturing had many shortcomings. The opportunity for improving this system arose when the manufacturing organization began to introduce a new computer-integrated manufacturing (CIM) system into their factories. This created an opportunity to standardize the way PWB designs were transferred into manufacturing.

##### Manufacturing Requirements Specification for PWB Designs

The first step of streamlining the design transfer process was to precisely understand what information manufacturing needs from design, and then standardize this information into a specification document. This process required a joint effort between the PWB CAD community and the manufacturing organization. The CAD manager championed this process and held several meetings with manufacturing engineers from the different factories. From this came a preliminary manufacturing specification for PWB designs, which is referred to as the CIM spec. The CIM spec. required considerable iteration, and will continue to be a living document which will naturally evolve with changing technologies and procedures.

Using this CIM spec., it was then possible to develop a standard manufacturing release package for PWB designers. This manufacturing release package consisted of several data files that would be stored in a standard format in a designated manufacturing directory. Manufacturing personnel could access this standard directory to find the latest releases of PWB designs, and the directory could be archived to ensure the integrity of PWB design data. All of the files comprising a manufacturing release package and the data contained in each are listed below:

##### 1. Panel file

The panel file contains all the panel design information needed by the factory CIM system. The file is arranged in a standard format that can be read by the CIM software.

## 2. Board file(s)

The board file contains all the board design information needed by the factory CIM system. The file is arranged in a standard format that can be read by the CIM software. Because boards are always released as part of a panel, a separate board file exists for each different board in the released panel.

## 3. Board graphics file(s)

The board graphics file contains a graphical image of the board in a standard graphics format. Two of these files exist for each board (one for each side.)

### Software Automation of Manufacturing Release

The manufacturing release package standardized the way that design information would be presented to the factory CIM system. The next step was then to develop a simple, standardized way to create the manufacturing release package from a PWB design. Unfortunately, the information required in the release package was not generally stored in the CAD system in a consistent manner. The different PWB designers each had different methods of representing design information in the CAD system. The first step in solving this problem was to quantify and standardize the way necessary design information would be represented. This resulted in a standard set of procedures that PWB designers would use when setting up design databases.

A PWB design database basically consists of a set of computer files. When the standard procedures for setting up a design database are followed, the necessary design information automatically appears in a standard format in the appropriate computer files. Standardizing the PWB design database allowed for the creation of a software utility that could search through the appropriate files in the PWB design database to find all of the information that is required to complete the manufacturing release package.

This software utility was developed as the combination of a computer program called CIMTRANS, written in C, and a UNIX shell script called rel\_to\_mfg. A PWB designer can execute rel\_to\_mfg on a CAD workstation to automatically release a PWB

design package. Figure 4.1 illustrates how CIMTRANS and rel\_to\_mfg generate a PWB manufacturing release package.

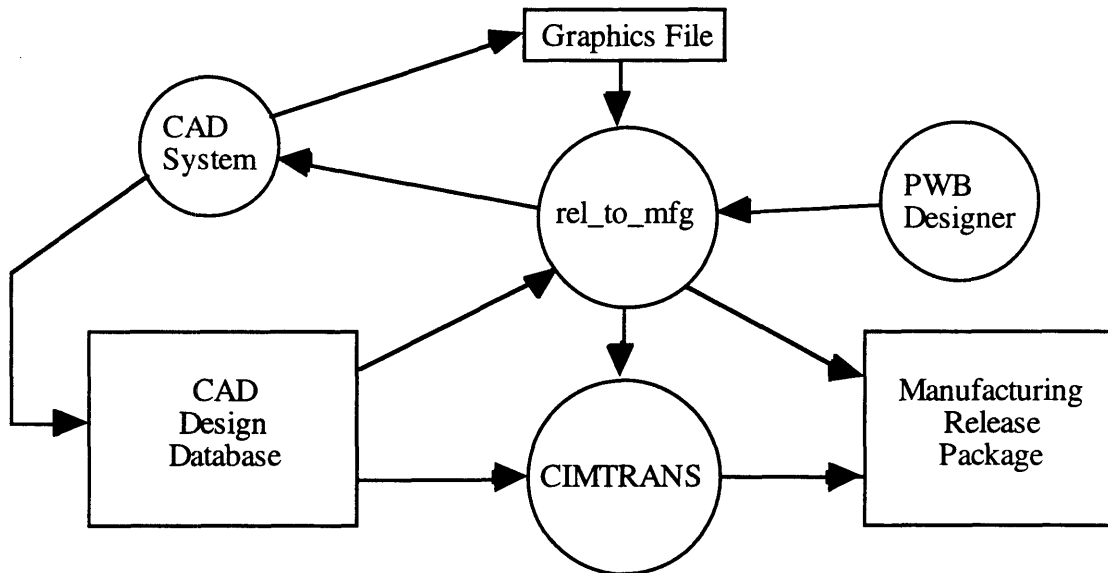


Figure 4.1. Generation of a PWB Manufacturing Release Package.

The script, `rel_to_mfg`, asks the designer for any necessary information that is not already stored in the design database, and it calls CAD system routines to generate updated files of relevant design information. This information is stored in four different files. The file, `mfg_info`, in the PWB design directory, contains information not available in any standard CAD database files. The files called `board` and `panel`, written to a temporary directory, contain standard CAD information on board and panel data. Also in the PWB design directory, a file called `comp_file` contains information about all the components of the PWB assembly.

After generating the necessary files, `rel_to_mfg` calls the program, `CIMTRANS`. `CIMTRANS` reads the components file, the panel and board files, and the `mfg_info` file and generates the panel file and board files described above which make up part of the manufacturing release package.

After CIMTRANS has generated the standard CIM files, rel\_to\_mfg removes the CAD board and panel files from the temporary directory. rel\_to\_mfg then informs the PWB designer that the design was successfully released, so the designer can notify the responsible manufacturing engineer.

#### 4.4 IMPROVED PROCESS SUMMARY AND ENHANCEMENT OPPORTUNITIES

Developing a standard manufacturing specification for design releases, standardizing the way necessary design data is stored in the CAD system, and automating the generation of the manufacturing release package greatly simplified the process of introducing new PWB designs into manufacturing.

The new transfer process does not contain nearly as many manual and error-prone steps as before. The fact that design data and manufacturing configuration data are now standardized will also improve data management problems and should facilitate future process improvements.

There are a few areas, however, where the system can still use improvement. Because under the new system, all the different sources of data are much better controlled, there should be new opportunities for tracking process errors. A pareto analysis could identify the most common errors, and a system could be put into place to automatically check for these common errors. The utilities, CIMTRANS and rel\_to\_mfg, could be easily expanded to perform checks of design data before the PWB package is released to manufacturing.

## **5.0 A METHODOLOGY FOR PRODUCT DEVELOPMENT PROCESS BENCHMARKING**

This chapter was written in collaboration with Rosaline Gulati, an MIT Master's candidate and Steven Eppinger, a Professor at MIT's Sloan School of Management. The chapter addresses an important area in which companies can improve their product development practices. In order to become or remain world-class competitors, organizations need to develop skills and practices for learning from themselves and from other successful companies. We describe a methodology for benchmarking product development practices. The method is illustrated using a case study involving two successful electronics firms. Their comparison points out important differences in organization, procedures, and culture, from which both parties can learn a great deal. We generalize to suggest how other organizations can follow a similar approach to benchmark their own product development processes. We conclude the chapter with suggestions for how to enhance this methodology through further research.

### **5.1. INTRODUCTION**

Companies today are becoming increasingly aware of the importance of product development as a key to their success. The accelerating pace of technological advancement and the globalization of major markets is forcing companies to increase the number of new products and the rate of product introductions. Product development process improvement and cycle time reduction are almost universally identified as critical strategic elements.

Because of the strategic importance of product development, it is vital that companies use benchmarking to evaluate their product development processes. Benchmarking can provide insights into product development at many different levels from the organization of development teams to the methods of performing specific technical tasks. For example, many companies struggle with the tradeoff between functional and

product-based development teams. Functional teams facilitate technical expertise and improve technology transfer between products while dedicated product teams bring the project closer to the customer. Benchmarking allows a company to learn about different ways to organize teams without the risk and time delay of running a pilot program.

This paper describes a methodology for benchmarking product development activities. An example is given of a product development benchmarking effort between two major electronics companies. Major points of comparison covering organization, procedures, and culture are described. This comparison identifies major opportunities for learning between the two firms. The paper also covers a generalized benchmarking process that firms can apply to their own product development processes. The paper concludes with a discussion of enhancements to the benchmarking process and recommendations for future research.

## 5.2. BENCHMARKING PROCESS FOR PRODUCT DEVELOPMENT

This section describes a generic process for executing a product development benchmarking study. The outlined steps cover issues important to most benchmarking efforts from identifying the need for benchmarking to completing a final project report. Specific benchmarking studies may be more or less complicated than the process outlined below. A less detailed study could omit some of the steps, while a more detailed study could require more elaboration or iteration over certain steps.

### 5.2.1. Generic Steps for Product Development Benchmarking

#### *Step 1. Identify a Need for Improving Product Development Processes*

Whether a benchmarking opportunity in product development is identified from within a company or by an outside entity, the first step is to find some aspect of the development process that needs improvement where information from another organization



could help. Most companies can easily identify major improvement opportunities in their product development activities. These opportunities can vary from improving the overall structure of a development effort to implementing a specific product development tool. It can be challenging, however, for individuals within a firm to recognize that significant learning can be gained from examining outside organizations.

### *Step 2. Identify Organizations for Benchmarking*

Choosing the right partner for a product development benchmarking effort naturally requires some understanding of the specific improvements that are desired. Once these have been identified, finding the right partner can require significant effort. The first step should be making an exhaustive list of candidates. These can be found through literature searches, professional societies, academic contacts, or suppliers. Ideally, the candidates would be in similar industries and would not be direct competitors. This would depend, however, on the focus of the benchmarking. If the study is intended to cover broad organizational issues, it may be appropriate to talk to a competitor. If, on the other hand, the goal is to learn more about a specific process or technology, a direct competitor would probably not be willing to share their knowledge. In this case it might be appropriate to look outside the target industry.

Once an adequate number of potential benchmarking partners is identified, more detailed information on each should be gathered. This can be done through phone calls or formal surveys. This process will not only help to find the best partners, but it will also identify interested individuals within the target organizations. After this preliminary search, a few primary targets should become evident. These organizations should possess the knowledge you seek, and they should express some interest of their own in the benchmarking study. The final list of organizations to be included in the study can then be selected from the final candidates. Depending on the goal of the study one or more partners

can participate. It is usually difficult, however, to coordinate meetings and agreements when more than two partners are involved.

### *Step 3. Identify Champions Within Organizations*

A benchmarking study involves activities like organizing meetings, writing reports, analyzing data, and giving presentations. To organize all of this work and provide the proper resources individuals within each organization have to be identified as champions. These individuals should ideally be product development managers or general managers with specific interest in the results of the study.

### *Step 4. Identify Major Objectives for Benchmarking*

The major goals of the benchmarking effort should be pretty well understood after completing the process of initiating the study and identifying the partners. After the champions are identified, however, the participants should get together and verbally agree on the overall objectives. These should be specific to each of the participants as each party will have different goals from the study.

### *Step 5. Develop Preliminary Benchmarking Proposal*

After champions have been identified and each participant has a good understanding of their goals, a benchmarking proposal should be written. This can be one document or customized documents for each participant. Figure 5.1 below lists some of the major items that should be included in a benchmarking proposal. The purpose of the document is to solidify the goals of the project among the participants, to allow the champions to get formal approvals within their organizations, and to help participants line up resources necessary to complete the study.

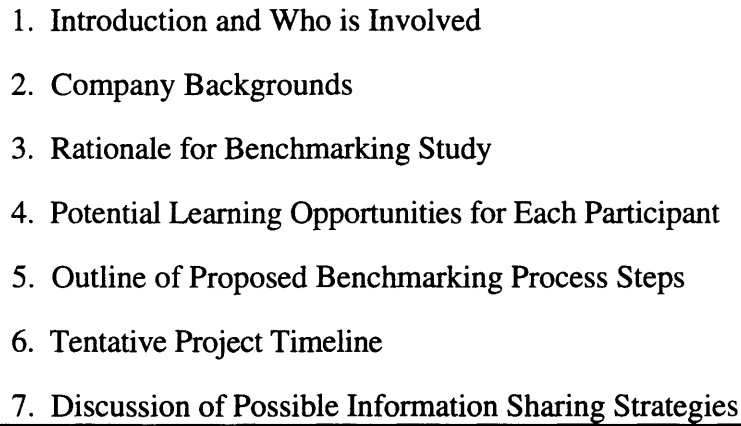
- 
1. Introduction and Who is Involved
  2. Company Backgrounds
  3. Rationale for Benchmarking Study
  4. Potential Learning Opportunities for Each Participant
  5. Outline of Proposed Benchmarking Process Steps
  6. Tentative Project Timeline
  7. Discussion of Possible Information Sharing Strategies

Figure 5.1. Benchmarking Proposal  
Important Items to be Included

*Step 6. Meet With Champions From Participating Organizations to Discuss Proposal*

Meetings should be held at all the participating organizations to discuss the proposal. This allows the champions from each organization to give feedback on the proposal to ensure that the benchmarking study will address all important issues.

*Step 7. Discuss, Revise, and Approve Proposal*

Inevitably, the benchmarking proposal will require some revision as it gets circulated through the partner organizations. Timelines and project details will change as resources are committed. This process is critical to the success of the study, but it is important to have an approval deadline for the proposal so that the project does not lose momentum.

*Step 8. Perform Benchmarking Meetings at Partner Companies*

Depending on the scope and scale of the benchmarking proposal, the benchmarking meetings can occur over a period of days, weeks, or months. The participants may meet face to face or share ideas, or they may perform specific tasks together to get very detailed information. The participants must balance the need to spend enough time to get necessary information without committing more resources than can be afforded.

*Step 9. Develop Preliminary Benchmarking Report*

The results of the project meetings must be summarized into a benchmarking report for distribution to the interested parties in the participating companies. This report will probably have to be revised to make sure it does not formally reveal sensitive information.

*Step 10. Set Up Follow-Up Meeting With Champions From Companies*

In order to revise and approve the final report, the champions will probably have to meet one final time. This will be an ideal time for the participants to reflect upon the benchmarking effort. They can clarify important points and possibly discuss new opportunities for benchmarking that came up from the now completed study.

*Step 11. Complete and Distribute Final Report*

Final report revisions can be completed remotely, and after final management approval, the final report can be distributed to interested parties in the partner organizations.

### 5.3. EXAMPLE BENCHMARKING STUDY

#### 5.3.1 Description of Benchmarking Process Used in this Study

The product development study described in this paper was performed by the authors, who are students of Professor Steven Eppinger at MIT's Sloan School of Management. Tom Abell was performing a research project at Company B and Rosaline Gulati, an employee of Ford Electronics, was beginning a research project with Professor Eppinger. The authors' familiarity with the two companies led them to realize that there was a common interest in benchmarking as well as some interesting points for comparison.

The specific benchmarking process that we used basically follows the generic steps that we outlined in Section 5.2.1. Figure 5.2 describes the overall flow of our process, and these steps are elaborated in the following section.

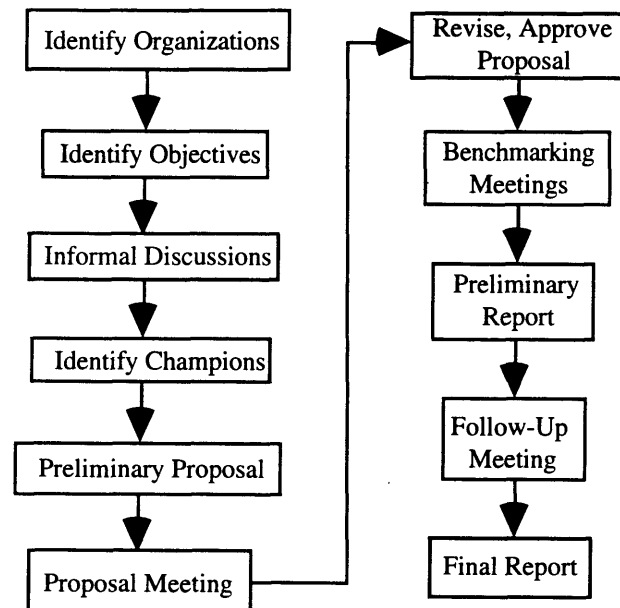


Figure 5.2. Benchmarking Case Study Process Flow

### 5.3.2 Benchmarking Steps

#### *Step 1. Identify Organizations for Benchmarking*

In our case, the organizations were identified from the common links between the authors. The benchmarking project appeared promising because of some important similarities and differences between the two organizations, Ford Electronics Division (ELD) and Company B. For comparison, both were similar in size and develop similar products. They also face similar challenges with the introduction of new technologies and dealing with international manufacturing sites. For contrast, the two organizations differ in their product development team structure and product timing requirements.

#### *Step 2. Identify Major Objectives for Benchmarking*

The major objectives evolved from the overall comparison of the two companies. We hoped to determine how the organizational differences influence the product development processes in each company.

#### *Step 3. Informal Discussions With Organizations*

Several phone conversations and meetings were held with product development managers in both companies to learn whether there was any interest in benchmarking.

#### *Step 4. Identify Champions Within Both Organizations*

From the informal discussions, two or three individuals were found in each company. At Ford, the champions were a product development manager, a product development process manager, and a CAE manager. The Company B champions were a development manager, a CAD support manager, and an information systems manager.

These individuals were all interested in the benchmarking project and were willing to get the project approved and help set up meetings.

*Step 5. Develop Preliminary Benchmarking Proposal*

The authors developed two preliminary proposals, one for each company, based on the informal discussions with the company champions. The proposals contained the following information:

- Background
- Description of organizations
- What both companies expect to gain from benchmarking
- Proposed topics to be included in the study
- Proposed topics to be excluded from the study
- Tentative Project Timeline

*Step 6. Meet With Champions From Participating Organizations to Discuss Proposal*

Meetings were held with the champions in both organizations to discuss the proposal. The discussion topics were refined based on the specific interests of the champions. Tentative meeting dates were outlined.

*Step 7. Revise and Approve Proposal*

Revised proposals with updated timelines were submitted to both companies for final approval.

*Step 8. Perform Benchmarking Meetings at Both Companies*

The authors met with various product development personnel from each company to cover the proposed benchmarking topics. These meetings took place over two or three days at both of the company sites. The interviewees included electrical and mechanical

development managers, manufacturing managers, and engineering and process support managers. Meetings lasted from one to two hours with each individual.

*Step 9. Develop Preliminary Benchmarking Report*

The results of the project meetings were summarized into a benchmarking report which was distributed to the project champions at both companies.

*Step 10. Set Up Follow-Up Meeting With Champions From Both Companies*

The project champions from both companies and the authors met at one of the company sites to discuss the contents of the report.

*Step 11. Complete Final Report*

Issues from the follow-up meeting were revised in the report, and the final report was submitted to both companies for final approval.

5.3.2. Ford Motor Company Electronics Division

Organizational Background

Ford Motor Company's Electronics Division (ELD) is part of Ford's Automotive Components Group. Hence, ELD's organizational management is structured almost parallel to other Ford Motor Company divisions. Ford Electronics offers design, development and manufacturing capabilities in powertrain and vehicle control systems, instrumentation and driver information systems and entertainment/communication systems for automobiles. ELD designs and manufactures electronic circuitry for these products and designs plastic and metal housings which are manufactured by outside suppliers. Products designed by ELD must last for the entire lifetime of the individual vehicles, which is typically 6 to 10 years. Products are typically produced in high volumes for 3 to 5 years, while replacement components must be available for several years beyond that.



ELD has about 300 major programs and close to 1000 minor ones. About 10% of these programs involve dedicated, collocated teams. ELD is headquartered in Dearborn, Michigan and has manufacturing sites in Brazil, Canada, England, Mexico, Portugal, Spain, United States and Wales.

The Electronics Division's customer base begins with Ford North American Automotive Operations Group (design, product engineering, assembly, and sales in North America) and terminates with the end consumer. In addition, ELD engineers must regularly interact and compromise with several internal Ford organizations (intermediate customers) in order to insure vehicle system compatibility before its products are released to the public.

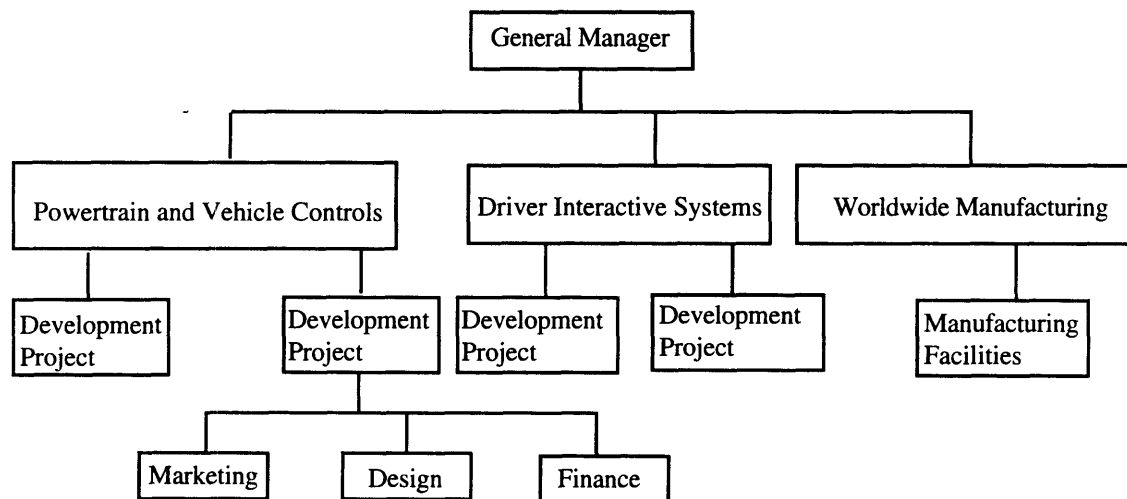


Figure 5.3. Ford ELD Generic Organization Structure.

#### Product Development Process and Structure

ELD is currently integrating all of their programs into a new product development process. There are whole departments at ELD that deal only with supporting this new product development process. We specifically talked to two of these departments, a

mechanical design support group and an electrical design support group. In this paper, we will describe ELD's product development process as was described to us by ELD management and engineering.

#### Product Development Teams

Product development teams at ELD are largely inter-departmental. A department at ELD is typically comprised of people with a specific set of skills. Departments at ELD vary greatly in organization and in size. Some are functionally organized, others are product-based. Hence the sizes can vary anywhere from 20 to even 60 or more. The systems groups tend to be organized in a matrix structure such that product development team members report primarily to their product supervisor and secondarily to a functional manager. Whereas the component group engineers generally report to a supervisor in the normal Ford manner.

Product development teams themselves may encompass a wide variety of people including a team leader, an ELD program manager, an applications engineer, a business planner, a Finance person, a Program Timing and Release person, a systems engineer, a product engineer, a Quality Office person, a manufacturing engineer, an Engineering Technology Development person, a Supply Office person, a Training person, or an outside suppliers. The size of a product development team varies anywhere from about 5 to 12 fully dedicated team members. Oftentimes, team members may be assigned part-time. Team leaders, assigned by management, are usually experienced engineers. Each team member is given very specific responsibilities during each phase of ELD's product development process.

#### Rewards and Recognition

Ford Electronics system of rewards is compatible with that of Ford Motor Company. Employees are reviewed about once a year, at which time they may receive either a merit raise or a promotion, based on their past performance. Employees are

congratulated by their management for a job well done. Occasionally, if a product development team does an exceptional job, the team members will receive small tokens of appreciation.

Recently, a new system to promote innovation at ELD has been established. As part of this program, employees may form teams with other employees of their choice and suggest specific improvements in the product development process. An employee whose suggestions are approved by upper management can accumulate points towards prizes offered by ELD.

### Communication

Information transfer occurs largely during regularly scheduled (weekly or bi-weekly) team meetings. Oftentimes, if a team is not entirely collocated, this is the sole opportunity that the team members have to meet. Informal communication typically occurs if team members are located in the same area. In addition, if other Ford divisions and/or outside suppliers have software that's compatible with ELD's, data transfer may occur electronically. Once a part is in production, most information transfer occurs electronically.

Overall communication at Ford Motor Company occurs via the Car Programs Management Division. This organization tracks each overall vehicle program timing by scheduling regular inter-divisional meetings.

### Program Timing

At Ford Motor Company, each vehicle program is on a very structured 48 month schedule from the "concept to the customer". During these 4 years, there are several prototype builds that are used as project milestones.

Most ELD product development projects are linked tightly to these car programs, which forces them to maintain a fairly rigid schedule. ELD's final product must be complete about 17 months before a vehicle goes into production.

## Product Development Tools

ELD uses a variety of software tools. The drafting department uses PDGS, which is compatible with the rest of Ford Motor Company. A few departments have begun to use ProEngineer for mechanical design. Currently, no other Ford divisions in the Automotive Components Group formally use ProEngineer. Intergraph is generally used for electrical schematic capture and PWB layout. Several circuit simulation and analysis tools are also used for electrical development.

Other very integral tools at ELD include Finite Element Analysis (FEA) and Ford developed FMEA (Failure Mode Effects Analysis). A typical ELD engineer often uses both the FMEA and FEA during the product development process.

## Major Product and Manufacturing Technologies Used

At ELD, products are usually assembled at the component level at which they are sold. If the product is a system of ELD components, ELD is typically very involved in the entire manufacturing process. If the product is a single ELD component, the IC technologies and circuit boards are usually designed and manufactured by outside suppliers with direction from ELD engineers. Finally, there exist some products which are wholly engineered and manufactured by outside suppliers. For these items, ELD engineers integrate them into the vehicle system.

## Prototyping Process

The prototyping process at ELD is relatively informal. Major milestones are geared toward vehicle program prototype builds for which ELD must provide up-to-date prototype components. Because the vehicle prototype process is on a very rigid schedule, many ELD prototype builds are scheduled so that products will be available for vehicle prototype builds. Other prototype builds are performed on an as-needed basis between vehicle

program prototypes. Generally, component prototypes are made by outside suppliers until ELD manufacturing facilities are ready to produce them.

## Metrics

Product development metrics are a very important way of benchmarking the product development process at Ford Motor Company. At ELD, one important factor is the number of ELD parts returned during a customer's 3 year/36,000 mile warranty. Another major metric is meeting the program timing constraints set by Ford Motor Company's Car Programs Management Division. Typically, a program's timing is compared to its past timing to gauge improvement.

### 5.3.3. Company B

#### Organizational Background

Company B designs, manufactures, and markets electronic products for worldwide markets. Their headquarters, containing marketing, product development, and most domestic manufacturing, is located in the U.S. There are several other manufacturing sites throughout the world. Company B designs and manufactures electronic products using the latest technologies in electronics manufacturing. Plastic and metal mechanical components are designed by internal development groups and are manufactured by outside suppliers. Typical market life cycles are 2 to 4 years, but individual products are designed to strict durability requirements so that they will last for 5 to 10 years of normal operation.

#### Product Development Process and Structure

##### Product Development Teams

Development teams at Company B are functionally organized. Usually either the mechanical or the electrical manager will informally assume the role of project leader,

tracking schedules and setting up project meetings. Development projects vary tremendously in scope and complexity.

#### Rewards and Recognition

Company B employees receive yearly performance reviews which help determine promotions and pay raises. Within Company B informal incentive programs exist where individuals can get small rewards like parties or trips for individual or team achievements.

#### Communication

Communication in development teams is very informal except for regularly scheduled project meetings. There is usually a weekly project meeting, and there can be additional weekly meetings for manufacturing, marketing, mechanical design, and electrical design.

Engineering personnel on a given project are usually located in the same area of the building. Manufacturing personnel are stationed in offices adjacent to the factories because their primary responsibility is to provide engineering support to the manufacturing operations.

#### Program Timing

Program timing is very fluid; engineering direction is often changed during the course of the project. Quality is the most important driver for manufacturing release.

#### Product Development Tools

The company uses one system for electrical design and another for mechanical design. Designers are mostly assigned to program teams instead of central design departments. The responsibility for introducing new product development tools is shared between CAD support groups and the individual development groups. Development managers decide which tools their team will use, but support groups are most up to date on

the availability and functionality of new tools. Sometimes, corporate or divisional advanced technology groups supply expertise to help bring in new technologies. Committees of development and support people are also formed to study the feasibility of new tools. Usually once a recommendation is made, tools are introduced through pilot programs.

#### Prototyping Process

Prototypes are often used as project milestones. Building prototypes allows the entire product development team to focus on the product.

#### Metrics

The company formally tracks few product development metrics. Overall project timing is continuously followed and updated. Management also generally tracks the number of engineering personnel dedicated to each program, but this is complicated by the fact that engineers usually work on more than one program at a time.

#### 5.3.4. Major Points of Comparison

##### Culture and Organization

Some of the most interesting points of comparison between the two companies revolved around their basic cultural and organizational differences. Company B's organization is very flat and there are few staff organizations for improving product development tools and processes. Interaction between different functional groups in a program is informal and relatively unstructured. Ford ELD, on the other hand, is closely tied to the Ford automotive culture and organization. Ford has groups dedicated to process improvement and coordination, and interaction between functional areas is coordinated by a program management organization.

## Product Development Process

An important difference between Company B and ELD is the way the development process is managed and improved. At Company B there are no staff groups responsible for development process improvement. ELD, on the other hand, has a department dedicated to studying, documenting and improving the product development process. At Company B, new development tools and techniques are introduced by individual product teams or through efforts of joint committees. ELD dedicates groups to study new tools and provide advanced analysis expertise to program teams.

## Program timing

At Company B product development schedules are often difficult to maintain because engineering direction is often changed during the course of the development effort. ELD programs, on the other hand, are strictly scheduled to coincide with the new car programs of Ford. The car program mandates prototype readiness timing and generally requires that the development of ELD components is complete as early as 17 months before their associated car programs. At Company B new development projects are relatively independent of one another, and management prefers to have flexibility to continuously redirect programs in response to changing market conditions.

## Technological Push

One important difference between ELD and Company B is the fact that ELD must be more conservative with new technology than Company B. The electronic components of automobiles must last for the lifetime of the car and must not jeopardize the timing of a new car program. While Company B maintains a superior quality image, their products do not have long product life cycles.



## Manufacturing Involvement

One contrast between Company B and ELD is the way development communities interact with manufacturing. Most of Company B's domestic manufacturing is performed at one site. This is also where most product development is done. ELD in contrast has most prototype manufacturing done by outside companies. Coordination with external manufacturing sites is done through on-site manufacturing representatives and factory-specific manufacturing guidelines.

### 5.3.5 Recommendations for Further Research

Our recommendations for more study with these particular companies are the following:

- 1) Communication between manufacturing and engineering after a product goes into production.
- 2) Technology reuse and how it can be effective.
- 3) Expanding the study to other similar electronics firms using this methodology.
- 4) The effects of corporate structure (culture) on converting to a new product development process.
- 5) The follow up process when parts are returned for warranty or issues arise during the manufacturing process.
- 6) The management structure of the manufacturing sector (union vs. non-union etc.)
- 7) How to integrate innovative changes to a product during the middle of the product development process (when the "innovation" phase is over).

## 5.4. CONCLUSIONS AND IMPROVEMENT OPPORTUNITIES

### 5.4.1. Analysis of Results

We felt that the method we used to benchmark these two companies' product development processes was effective mainly because we specifically defined our goals in our initial proposal.

We noted several interesting results from our methods. First, by having each organization explain their product development process in detail, they learned not only about the other organization's product development issues, but also more about what their own organization was doing. Second, a product development process designed for components is vastly different than a product development process for a system of components. We found that any generic product development process must be carefully tailored up front in order to be effective. Third, as an organization grows larger and expands its manufacturing to off-site locations, it seems necessary that they can function more efficiently with a formalized product development process. And, finally, electronic data exchange can be used to greatly facilitate information transfer. The initial training time spent to learn these software tools is time very well spent in the long run.

### 5.4.2 Recommendations for a Successful Benchmarking Study

Our recommendations for performing a benchmarking study of product development are as follows:

- 1) Be specific when defining the goals of the study.
- 2) Begin the study with two companies with similar problems or products.
- 3) Repeat the basic benchmarking steps we outlined in Section 5.2.1.
- 4) If no intermediaries like the authors are available, an alternative is to have direct meetings between the two companies.

- 5) If one desires to study specifics, it is useful to have a specified set of metrics (at intermediate points as well as at the end) by which to gage the product development process.
- 6) Do periodic benchmarking studies, similar to ours, not only to gage company performance, but also, to encourage product development team members to describe their process and hence learn about other implementations of the same generic process within their own company.
- 7) Get a perspective from upper management as well as from product development team members. This can be used to gage how well the current product development process is accepted within the company.



## **6.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH**

### **CONCLUSIONS**

This thesis describes three major areas of contribution: evaluating one company's product development process, implementing an improved method of transferring PWB designs to manufacturing, and performing a product development process benchmarking study between Ford Electronics and that company. These three areas of focus provided different types of contributions varying from measurable, applied benefits to more abstract and academic benefits.

The PWB design transfer project provided a very tangible contribution to the company.

The current process, requiring manual data transfer and data entry, leaves many opportunities for errors. The creation of a standard specification for CIM releases will also allow better communication between all of the design groups and manufacturing groups throughout the organization. The result should be higher quality in the development process.

The benefits of the product development process study are much less tangible than the PWB design project because the problem is much larger. The company is committed to making product development process improvements like increased quality and reduced cycle times. The process evaluation effort in this thesis provided the company an outsider's perspective on their overall product development activities. The design structure matrix representation provided a new look at familiar product development issues. The internship project helped establish important relationships within the development community that will continue through ongoing process improvement efforts.

The product development benchmarking study between the company and Ford Electronics outlined a generic benchmarking methodology, and it illustrated distinct

organizational differences between the two companies. People at both companies gained different perspectives on common problems. The study highlighted the advantage of having prototype manufacturing done at the same site as development engineering. It also illustrated the tradeoff between process flexibility and maintaining schedules in development projects. Ford Electronics must strictly maintain project schedules because they are tied to large vehicle programs. This requires more conservative timing and staffing of programs and larger project management staffs to track progress. The company where I interned, on the other hand, develops many products that are relatively independent. This allows the company to continuously reevaluate and redirect programs and resources in response to market needs. On the other hand, it also means that program schedules can be difficult to maintain, making planning and forecasting difficult. The real cost of delaying programs, however, should include the loss of revenue associated with a shorter market lifetime which is generally difficult to calculate.

## RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis focused mainly on the prototyping phase of an electronic product development process. The main recommendations for developing and tracking metrics, streamlining prototyping processes, and introducing more computer-aided engineering tools will yield the most improvement in the areas of mechanical and electrical development. There are some other important issues that were not covered in this thesis that also have significant influence on the success of product development efforts. These issues, which are described below, also deserve considerable attention.

### Software Development

The product development assessment in this thesis focused on mechanical and electrical development. A few major trends are making software development increasingly important relative to other activities. First, electrical components are becoming more highly

integrated, meaning that individual chips are performing the functions that used to require several chips. This will tend to reduce the demands on electrical development personnel.

So the general trend in electronic product development is toward common electrical designs that contain relatively few highly-integrated components and are differentiated using software features. As this happens, the software development activities will become much more important to the success of new development projects. This may require significant changes to the structure and flow of development efforts.

### Development Funnel

The process of identifying new product opportunities and choosing which of those will become full-fledged development projects is called the development funnel by Wheelwright and Clark [1993]. They emphasize the development funnel to their clients as one of the most important aspects of the development process. This is where the most significant attributes of each new product are defined, and this is where companies decide what mix of new products they will offer. This thesis did not address the development funnel at the company. Studying the development funnel requires information such as product costs, technology initiatives, development budgets, market forecasts, and competitor strategies that would not be appropriate to publish in an academic thesis. It is important, however, to emphasize that optimizing the process of engineering a new product is not valuable if the new product is not the right product for the market. There are several aspects of the development funnel problem that could represent significant improvement opportunities for the company.

The first step for improving the development funnel, according to Wheelwright and Clark, is to understand and formalize the process of identifying new product opportunities. As the market matures, it will be more important to inject customer preferences into the very early stages of product development. Conceptual development will no longer focus primarily on cost and technology. A structured, customer-needs identification process may

become an important step for new development projects. Burchill [1993] describes such a process called Concept Engineering which uses surveys and benchmarking to develop product concepts that better satisfy customer requirements. The now famous House of Quality [Hauser and Clausing, 1988] has been used for many years by companies like Ford and Xerox translate customer needs into engineering requirements.

Another aspect of the development funnel that may deserve attention at the company is the allocation of engineering resources across development projects. Wheelwright and Clark mention that almost every company tries to take on more development projects than they can possibly achieve. The problem is that talented development resources are always scarce and that every new product recommended by marketing is considered essential. The key to solving this problem is to understand how resources are allocated across the range of product programs and to make sure that the proper mix of programs is initiated.

#### Focused Benchmarking

The benchmarking effort in Chapter 5 focused on high-level issues like communication, organizational structure, and process flow. These issues were more appropriate for a published academic thesis than specific technical needs. Many of the product development challenges facing companies like the company where I interned are shared by other companies in different industries and different markets. The opportunity for benchmarking exists even for very specific problems like introducing particular CAE tools. These opportunities can be pursued using the methodology outlined in Chapter 5, with the understanding that the results may not be suitable for publication. It is possible, for example, that two companies that do not compete could share otherwise sensitive information.



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